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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2320

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I - EFFECT OF SOLUTION-TREATING TEMPERATURE

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SUMMARY

An investigation was conducted to determine the effect of solution treating at temperatures of 2350°, 2250°, and 2100° F followed by aging at 1500° F on the life of small cast AMS 5385 gas-turbine blades. The blades were operated in a small gas turbine. The temperature and the centrifugal stress at the midspan of the blade airfoil were 1500° F and 20,000 pounds per square inch, respectively.

The results of this investigation indicated that the mean life was improved and the time to initial failure of as-cast AMS 5385 turbine blades was lengthened by the heat treatments used. These results were confirmed by a statistical analysis. The results also indicated that some of the heat treatments resulted in improved uniformity. Statistical analysis, however, indicated that these improvements may have been due to chance.

INTRODUCTION

The short life of turbine blades in service to first failure has considerably limited the length of time to first overhaul of jet engines. Currently used cast heat-resistant blade alloys have relatively short first-failure times and mean lives as well as poor uniformity of performance (reference 1). Some investigators have shown that the high-temperature strength and blade life could be improved by heat treatment (references 1 to 3). An investigation was made at the NACA Lewis laboratory to determine the effect of a series of heat treatments on mean life, uniformity of performance, and first failure time of cast turbine blades of a particular alloy and to observe the types of metallurgical structure associated with the various treatments and changes in structure during operation.

The alloy selected for this investigation was a cobalt-chromium-base heat-resistant alloy, AMS 5385. This alloy was selected because it is a material of current interest and, as it is one of a class of cobalt-chromium heat-resistant alloys, results therefrom might conveniently serve as a base line for a study of the effect of variations in composition in this class of alloys on the optimum heat treatment.

Blades of this alloy were solution-treated at a series of temperatures and aged at the turbine test temperature. The blades were operated in a small gas turbine at conditions that resulted in a blade temperature of approximately 1500° F and a centrifugal stress at the blade airfoil midspan of approximately 20,000 pounds per square inch. Because comparatively small numbers of blades were used in this investigation, the results were subjected to a statistical analysis to determine their significance. Metallurgical examinations were conducted before and after operation to determine the effects of heat treatment and operating conditions on the cast alloy structure and to determine the mechanism of blade failure.

APPARATUS

The nominal composition of the AMS 5385 alloy (reference 4) is:

C	Mn	S	Cr	Ni	Mo	Fe	Co
0.20-0.35	1.00 max.	1.00 max.	25.00-29.00	1.75-3.75	5.00-6.00	2.00 max.	remainder

Blades were heat-treated in a helium atmosphere with the temperature controlled within ±10° F.

A small gas turbine supplied with hot gases from a turbojet combustion chamber was used to evaluate the performance of the turbine blades in this investigation. The turbine operating temperatures were indicated by a thermocouple located in the inlet duct about 12 inches upstream of the turbine. This apparatus is similar to that described in detail in reference 5 except that in the present investigation the turbine gas inlet was located at the top of the unit. A thin sheet of metal was placed around the turbine about 4 inches from the inner wall of the water-jacketed housing surrounding the assembly. The space between the shield and the housing was filled with an asbestos packing to prevent injury to sound blades by

ricocheting fragments and also to preserve the fragments. The turbine disk was about 9.5 inches in diameter and the blades extended about 1.5 inches beyond the disk periphery. Blades were fastened to the disk by a dovetail arrangement and secured by peening the blade roots. The wheel contained 71 long-necked and 71-short-necked blades, alternately spaced. Typical blades are shown in figure 1.

PROCEDURE

Blade Preparation

All blades used in this investigation were radiographed for internal flaws and visually examined for external flaws. The shrouds of the blades were ground to a uniform length, width, and thickness of 0.450, 0.270, and 0.070 inch, respectively, to eliminate shroud dimensions as a variable and to obtain a nominal centrifugal stress at the midpoint of the airfoil length of 20,000 pounds per square inch.

Five blade groups and their respective heat treatments are listed in table I. These blades were operated in a turbine and their performance compared with that of the as-cast AMS 5385 blades reported in reference 1. All blades were incorporated into the same wheel.

Turbine Operation

The turbine was operated in the following manner: Combustion air was supplied and the turbine was motored at approximately 6000 rpm for 5 minutes. Combustion was then started and operating conditions were achieved in approximately 3 minutes. The wheel was operated at the desired conditions of 22,500 $\pm$200 rpm and an inlet gas temperature of 1650 $\pm15^{\circ}$ F until blade failure occurred. Experience with this turbine has indicated that a gas temperature of 1650° F would result in a blade temperature of about 1500° F. The speed of 22,500 rpm resulted in a nominal centrifugal stress of 20,000 pounds per square inch at the midspan of the blade airfoil. Upon failure of a blade, as indicated by a change in the pitch of sound coming from the unit, air flow was quickly reduced to such a value that the turbine motored at approximately 6000 rpm. This air flow was maintained about 10 minutes in order to cool the assembly. Shutdowns were made quickly in order to minimize the effects of vibration caused by wheel unbalance.

The turbine wheel was then removed for replacement of the blades that had failed. Fractured blades were replaced with as-cast AMS 5385 blades of the same shroud dimensions to preserve balance conditions. Severely cracked blades were considered failures and also replaced in order to minimize shutdowns and risk of injury to sound blades by flying fragments. Records were kept of operating conditions and of blade condition at each shutdown. The wheel was balanced at the beginning of the investigation and then rebalanced whenever the amount of vibration was considered excessive.

Metallurgical Examination

All blades that had failed were examined to determine fracture-surface texture and oxide coloring. The blades were sectioned about 1/16 inch below and parallel to the failure zone and then mounted, polished, and electrolytically etched in 10-percent aqueous hydrochloric acid. The number of grains in the blade cross section was determined.

The Rockwell-A hardness of all blades that had failed and of two unused blades of each group was determined in the cross section 1/16 inch below the failure zone.

Areas of blade fracture were metallographically examined to determine the mechanism and the propagation of blade failure and to determine the changes in structure after heat treatment and after turbine operation. These specimens were electrolytically etched in a solution of 10-percent nitric acid plus 10-percent ethylene glycol in ethyl alcohol.

Statistical Procedures

Commonly used statistical equations were employed to measure the significance of any observed differences between each of the various groups of treated blades and the as-cast blades. These formulas are presented in the appendix.

RESULTS AND DISCUSSION

The results of blade performance are presented in table II. The values for the mean life, standard deviation (measure of uniformity of blade performance), first-failure time, and final-failure time are listed in table III. From the data in table III, the mean life was

improved by all treatments, with treatment 2 giving the greatest mean life (approximately 60 percent higher than that of the as-cast) of the treatments investigated. Heat treatment also improved the first-failure time for every group whereas only treatments 1 and 2 showed appreciable improvement in final blade life. The maximum final blade life was that of group 2, which was approximately 30 percent higher than that of the as-cast blades. As for uniformity, treatment 3, 4, and 5 showed an improvement in standard deviation; treatments 1 and 2 showed a reduction. The cumulative-frequency curves for the as-cast blades and the various treatments are compared in figure 2.

Because of the small number of blades per group used in this investigation, statistical analysis was applied to the results in order to determine whether the observed differences in mean lives and standard deviations between each of the heat-treated groups and the as-cast group were significant or a chance occurrence. This analysis using equations (3) and (4) of the appendix determines, for particular probabilities, theoretical limits within which the mean life and standard deviation for infinitely large groups of identical blades will lie. Use of this information for each treatment and the as-cast condition yields an objective appraisal of the effects of the particular treatment upon mean life and standard deviation. The results indicate that for a 99-percent probability the mean life of an infinitely large group of as-cast blades would be a maximum of 64.2 hours, whereas the mean life of an infinitely large group of heat-treated blades would be a minimum of 68.7, 71.5, 73.9, 58.8, and 65.4 hours for treatments 1 to 5, respectively. For a 95-percent probability, the maximum mean for an infinitely large group of as-cast blades would be 61.2 hours and the minimum mean life for an infinitely large group of blades with treatment 4 would be 65.2 hours. From these data, it can be determined that in all instances the observed improvements in mean life are significant and can be attributed to the heat treatments used. Statistical analysis revealed that the differences between the observed standard deviations for the heat-treated blades and the as-cast blades were not significant; therefore the apparent improvements in uniformity for treatments 3, 4, and 5 and the apparent reduction in uniformity for treatments 1 and 2 may have been due to chance. In order to compare the first-failure times of the alloys, corrected for sample size, the time at which 99.8 percent of the blades in an infinite sample still had not failed was computed. This value was arbitrarily taken as an index of the first-failure time of an infinite sample. These values are tabulated in table III and indicate that all treatments resulted in improvement in first-failure time over the as-cast blades. The order of improvement over the as-cast blades in first-failure times based on sample statistics from the best to worst were treatments 3, 5, 1, 4, and 2. The foregoing analyses assumed normal distribution of blade failure.

Typical blade failures from the various samples are shown in figure 3. The failure zone lies approximately at the midpoint of the airfoil length. Some blades of all five samples manifested necking, indicating that the blades retained some ductility after solution and aging treatments.

The textures of the blade fractures are exemplified by the surfaces shown in figure 4. The coarse crystalline surface shown was observed in all failures. The nature of the fracture surfaces of the heat-treated blades is the same as that observed for as-cast blades (reference 1) and similar to the stress-rupture-type of fracture of cast AMS 5385. The fracture surface of the blades was generally divided into two distinct zones of different oxide colors, one a dark gray and the other ranging from a light straw to a deep blue. The gray zone was found in the area where initial cracking was observed, whereas the other color zone was observed only on freshly fractured surfaces.

The results of the grain-size measurements indicated a wide variation of grain sizes among all the blades ranging from 2 to 10 grains in a blade cross section at the failure zone. No simple gross correlation could be found between grain size and blade life, which suggests that other variables may have masked the effects of grain-size variations. The effect of grain orientation upon blade life may have been more significant than the effects of grain size.

The hardness determinations of the five blade groups and of as-cast blades are presented in table IV. These results indicate that solution treatment decreased the hardness of cast AMS 5385. For the same solution-treatment temperature, the furnace-cooled blades were generally softer than the air-cooled blades. Aging increased the hardness of the blades solution-treated at 2250° and 2350° F about 9 units (Rockwell-A), whereas the blades solution-treated at 2100° F increased about 3 units. Strain and age-hardening resulting from turbine operation caused an increase in hardness of about 3 units (Rockwell-A) for groups 1, 2, 4, and 5, and an increase of 5 units for group 3. The as-cast blades increased about 8 units (Rockwell-A) in hardness during operation but were still slightly softer than all the heat-treated blades. No appreciable difference in hardness was found between the first and last blade failures of each heat treatment, indicating that hardening occurred before the first blade failure in all instances for the heat-treated blades.

The representative microstructures of the blades after solution treatment are compared with the as-cast microstructure in figure 5.

The as-cast structure of AMS 5385 (fig. 5(a)) consists of complex carbides (references 6 and 7) in a cobalt-rich solid-solution matrix. Some precipitated phase is evident in the vicinity of the grain boundaries. The structure of the primary carbides is shown in figure 6. Structurally the carbides apparently consist of a matrix and a precipitated phase or phases.

Following are the effects of solution treatment on the structure of cast AMS 5385:

Group 1 (fig. 5(b)): The complex carbides formed a shape that has been described as characteristic of melting (reference 3). Some of the carbides were nearly dissolved in the matrix and no grain-boundary phases were found.

Group 2 (fig. 5(c)): Some melting and solution of carbides occurred but they were not as severe as in the treatment for group 1. Along the grain boundaries a eutectoid phase similar to that described in reference 7 formed. Structurally, the eutectoid phase had a pearlitic appearance.

Group 3 (fig. 5(d)): This structure was similar to as-cast AMS 5385 except for a small amount of precipitate around the primary carbides. No evidence of any grain-boundary eutectoid phase was present.

Group 4 (fig. 5(e)): Some melting and solution of the primary carbides occurred. Furnace cooling, however, produced carbides of a more nodular shape. The eutectoid phase formed in the vicinity of the grain boundaries as in group 2 but covered a larger area and, in general, was coarser.

Group 5 (fig. 5(f)): The structure is generally the same as that of group 4. Some of the carbides are present in the form of small clusters of nodular particles, whereas the larger particles of carbide had single-phase structures and almost geometric shapes (fig. 7). The grain-boundary eutectoid was generally coarser than that of group 4. Clusters of fine eutectoid can be seen (fig. 7) at the outer edges of the coarse lamellar eutectoid.

The effect of the solution treatments on the cored structure of cast AMS 5385 is illustrated in figure 8. All the specimens shown were deeply etched for the same period of time to reveal the cored structure. The apparent precipitate shown in some of the structures is the result of the staining produced by the deep etch.

The structures shown can be compared only on a qualitative basis and indicate that solution treatment at temperatures of 2250° and 2350° F will eliminate the cored dendritic pattern to some degree. The detectable difference between the as-cast structure and the 2100° F solution-treated structure for group 3 is small. No apparent differences exist in degree of coring among groups 1, 2, 4, and 5.

The effects of aging after solution treatment are shown in figure 9. The structural effects of aging the solution-treated blades for 48 hours at 1500° F are as follows:

Group 1 (fig. 9(a)): Two phases formed: one dark gray enveloping the primary carbides, and the other a relatively coarse precipitate throughout the matrix. The precipitate appeared heavier in the vicinity of the carbides, which indicates that it was nucleated in these areas and that a concentration gradient probably existed in the vicinity of the carbides. The structure of the precipitate was both lamellar and nodular.

Group 2 (fig. 9(b)): A matrix precipitate formed as in group 1 except that the precipitated constituent was finer.

Group 3 (fig. 9(c)): A precipitate formed that was clustered around the primary carbides as in the as-cast AMS 5385. The particles were predominately nodular although some of the precipitate of lamellar structure was similar to the eutectoid phase.

Group 4 (fig. 9(d)): More of the eutectoid phase formed that appeared lighter in color and finer than the eutectoid formed during solution treatment. The new eutectoid areas occurred in the outer boundaries of the earlier formations. Some precipitate also formed in the matrix and clustered around the primary carbides.

Group 5 (fig. 9(e)): The effects of aging were the same as in group 4 except that the new eutectoid formed was finer and the matrix precipitate was more uniformly dispersed.

Solution treatment for 1/2 hour at 2250° followed by air- and furnace-cooling and at 2350° F followed by furnace-cooling - except in the case of group 1 (2350° F, air cooled) - resulted in the formation of a eutectoid phase in the vicinity of the grain boundaries similar in appearance to the pearlite found in steels. The number and the size of the lamellae formed is a function of temperature and cooling rate. After solution treatment the aging resulted in the formation of a precipitate. The location, the structure, and the quantity of precipitate formed is related to the solution treatment of the alloy.

Examination of the aged blades after turbine operation revealed that the change in structure which occurred consisted mainly of a slight increase in the amount of the matrix precipitate and possibly an agglomeration of the precipitate particles. Examination of the blades which had fractured revealed that the fracture paths were intercrystalline at the origin and after they had progressed through the blade for a distance, became transcrystalline. The nature of the crack propagation in the five groups is the same as that reported for the as-cast AMS 5385 blades of reference 1. Photomicrographs of typical blade cracks are shown in figure 10. Whether the crack propagation was prevented by the areas of eutectoid in some of the blades could not be determined.

In order to determine the effects of the various treatments, the effects of an aging treatment alone should be considered. The results of reference 1 revealed that aging cast AMS 5385 for 48 hours at 1500° F increased the mean life from 55.2 to 63.6 hours and decreased the standard deviation from 20.7 to 15.2 hours. A comparison of the effects of aging with the solution treatment plus aging, indicated that in every group the solution treatment resulted in further improvement of mean life. Statistical analysis of the various solution treatments reveals that in all of the cases except group 4 solution treatment significantly improved mean life over aging alone. The groups air-cooled after solution treatment had the highest mean lives. For each method of cooling, the maximum mean life was obtained at a solution-treating temperature of 2250° F.

On the basis of the metallographic examination previously described, the maximum improvement in mean life was obtained with a solution-plus-aging treatment that produced a structure containing a nodular precipitate dispersed throughout the matrix. Excessive melting of the primary carbides may have caused the lower mean life obtained for the groups solution-treated at 2350° F. These results are based on one solution-treating time (1/2 hr) and two cooling rates, (air cooling and furnace cooling, 500° per hr). Longer solution times and different cooling rates must be investigated before the optimum structure obtainable is determined.

When the aging-treatment standard deviation (15.2 hr) is compared with the results of solution treatment plus aging, none of the solution treatments resulted in improvement in uniformity over aging alone. The failure of all solution treatments to significantly improve uniformity over an aging treatment alone indicates

that, although the cored structure, which may be assumed to influence blade-life uniformity, was partly eliminated by some of the treatments (fig. 8), other variables still may result in considerable scatter of performance. Possible variables are grain orientation and the nature and the distribution of the precipitating phase and primary matrix carbides.

SUMMARY OF RESULTS

The following results were obtained in an investigation of the effects of solution treating at temperatures of 2350°, 2250°, and 2100° F followed by aging at 1500° F on both the life characteristics and the structure of small as-cast AMS 5385 gas-turbine blades:

1. The mean life was improved and the time to initial failure was lengthened by all the heat treatments. The improvement was confirmed by statistical analysis.

2. The uniformity was improved over as-cast blades by these treatments: 2350° and 2250° F, furnace-cooled, and 2100° F, air-cooled. Statistical analysis, however, did not indicate that these improvements were significant.

3. Solution treating modified the structure of cast AMS 5385 in the following ways: (a) Above a temperature of 2100° F, the nature of the primary carbides was changed as a result of melting or solution or both. A eutectoid phase was formed in the vicinity of the grain boundaries in the group solution-treated at 2250° F and air-cooled and in both the 2250° and 2350° F furnace-cooled groups.

4. The aging of the solution-treated blades in all cases resulted in the formation of a visible precipitate. The structure, the distribution, and the quantity of this precipitate varied with the prior solution-treating conditions.

5. Failures of blades of all treatments were intercrystalline at their origin and became transcrystalline as they progressed through the blades.

National Advisory Committee for Aeronautics,
Lewis Flight Propulsion Laboratory,
Cleveland, Ohio, October 2, 1950.

APPENDIX - STATISTICAL FORMULAS

The sample mean and the standard deviation are, respectively:

$$X = \frac{\sum_{1}^{N} x_i}{N} \tag{1}$$

and

$$\sigma = \sqrt{\frac{\sum_{1}^{N} (X - x_i)^2}{N}} \tag{2}$$

where

X mean blade life for group, hr

N total number of blades in group

x_i individual blade life, hr

σ standard deviation in blade life for group, hr

These statistics, when based upon comparatively small samples, are an approximation of the population mean and the standard deviation that would be obtained from an infinitely large sample. The limits within which the population mean and the standard deviation might lie, however, can be determined for a given probability based upon the data for the comparatively small samples. The following equation (reference 8) gives the probability that the population mean lies with a specified interval: (This equation assumes a normal distribution of mean blade lives.)

$$t = \frac{\sqrt{N}(\bar{X} \pm X)}{\breve{\sigma}} \tag{3}$$

where

t probability factor based upon Students t distribution for $n-1$ degrees of freedom

$\bar{X}$ either upper or lower limit of population mean life for given probability, hr

$\breve{\sigma} = \sqrt{\frac{N}{N-1}}\,\sigma$

Similarly, the following equation gives the probability that the observed values of sample standard deviation for any two normally distributed samples actually differ (reference 8):

$$L = \frac{(n_1 + n_2) \log_e \breve{\sigma}^2 - (n_1 \log_e \breve{\sigma}_1{}^2) - (n_2 \log_e \breve{\sigma}_2{}^2)}{1 + \alpha} \tag{4}$$

where

$n_1 \quad = N_1 - 1$

$n_2 \quad = N_2 - 1$

N_1 total number of blades in first sample

N_2 total number of blades in second sample

$\breve{\sigma}^2 \quad = \dfrac{N_1 \sigma_1{}^2 + N_2 \sigma_2{}^2}{N_1 + N_2 - 2}$

$\breve{\sigma}_1{}^2 = \dfrac{N_1 \sigma_1{}^2}{N_1 - 1}$

$\breve{\sigma}_2{}^2 = \dfrac{N_2 \sigma_2{}^2}{N_2 - 1}$

σ_1 standard deviation in blade life for first sample, hr

σ_2 standard deviation in blade life for second sample, hr

$\alpha \quad = \dfrac{1}{3}\left(\dfrac{1}{N_1 - 1} + \dfrac{1}{N_2 - 1} - \dfrac{1}{N_1 + N_2 - 2}\right)$

The value L has a χ^2 distribution with one degree of freedom, from which the probability that the calculated value of L may be yielded by a population is determined. The upper tail of the distribution is used as the region of rejection.

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TABLE I - HEAT TREATMENTS OF BLADES

[All samples aged for 48 hr at 1500° F]

Group	Number of blades	Treatment
1	18	Solution-treated 1/2 hour at 2350° F, air-cooled
2	18	Solution-treated 1/2 hour at 2250° F, air-cooled
3	18	Solution-treated 1/2 hour at 2100° F, air-cooled
4	17	Solution-treated 1/2 hour at 2350° F, furnace-cooled[a]
5	18	Solution-treated 1/2 hour at 2250° F, furnace-cooled[a]

[a]Cooling rate in furnace was approximately 500° F/hr.

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TABLE II - TIME TO FAILURE OF HEAT-TREATED AMS 5385 TURBINE BLADES

Time, hr				
Group 1 2350° F air-cooled	Group 2 2250° F air-cooled	Group 3 2100° F air-cooled	Group 4 2350° F furnace-cooled	Group 5 2250° F furnace-cooled
30.9	38.0	43.1	37.1	47.9
46.9	48.4	58.6	44.8	48.4
58.6	54.5	62.7	46.9	55.0
62.7	55.2	74.4	48.6	55.2
66.7	62.0	78.8	49.8	57.1
77.4	74.0	80.9	60.2	73.3
82.0	86.8	80.9	62.0	73.3
84.5	86.8	85.1	73.3	77.4
85.3	87.6	85.3	79.8	78.0
86.8	91.2	86.8	82.2	78.0
88.4	92.2	88.4	84.5	78.2
90.8	107.0	88.4	85.1	80.0
92.9	108.2	90.8	86.8	84.2
92.9	112.1	94.2	86.8	85.1
97.8	112.1	97.8	87.6	94.5
103.0	114.0	99.3	96.5	96.5
106.1	120.8	100.2	97.8	96.8
118.1	130.6	101.6		98.8

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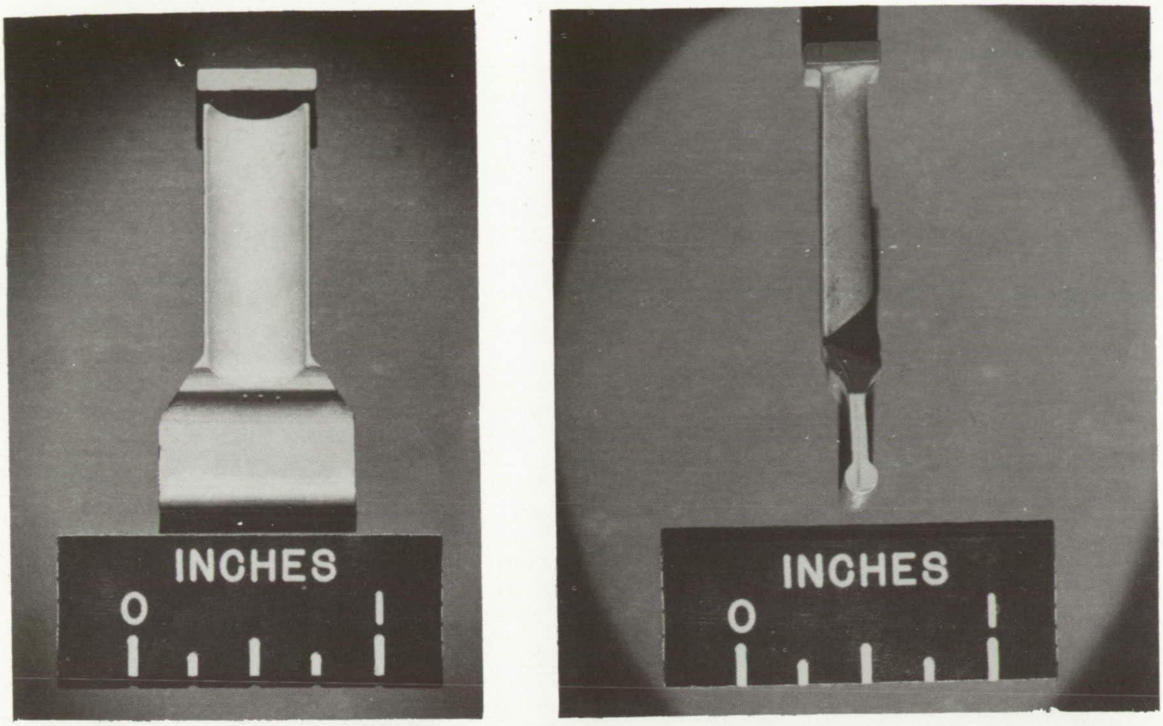
TABLE III - COMPARISON OF RESULTS OF PERFORMANCE OF HEAT-TREATED AND AS-CAST AMS 5385 TURBINE BLADES

Group	Mean life (hr)	Standard deviation (hr)	First-failure time (hr)	Final-failure time (hr)	Computed index of first-failure time (hr)
As-cast	55.2	20.7	4.3	98.8	0
1	81.8	21.1	30.9	118.1	16.7
2	87.9	26.5	38.0	130.6	6.0
3	83.2	15.0	43.1	101.6	37.0
4	71.2	19.2	37.1	97.8	11.8
5	75.4	16.1	47.9	98.8	25.6

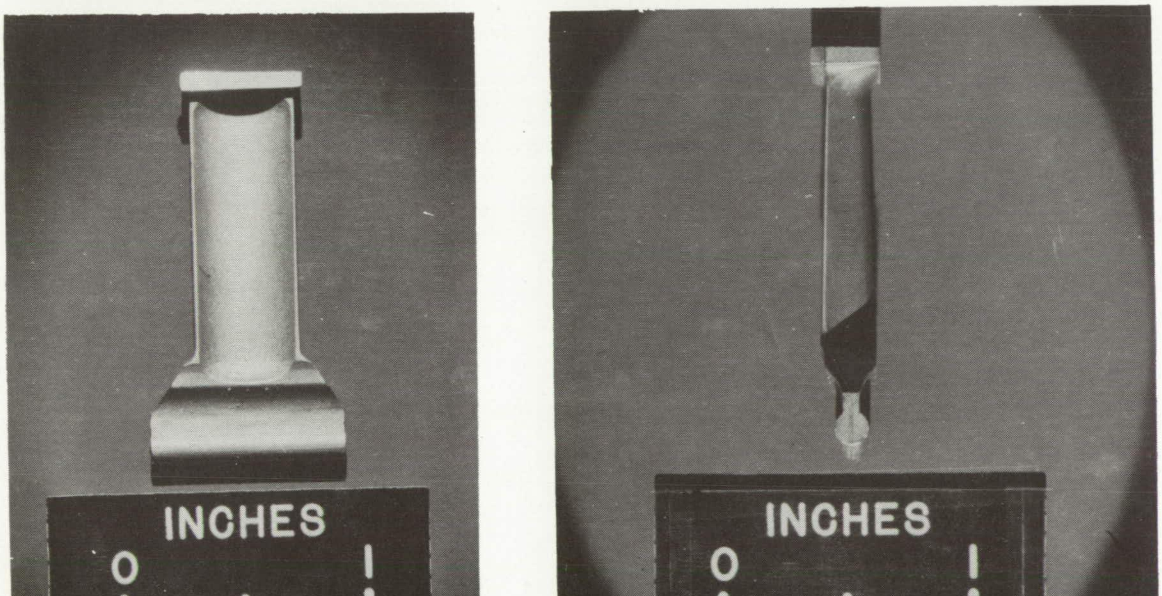
TABLE IV - SUMMARY OF HARDNESS DETERMINATIONS OF AS-CAST AND HEAT-TREATED AMS 5385 TURBINE BLADES

Group	Average Rockwell-A hardness[a]		
	Solution-treated	Solution-treated and aged	After failure
As-cast[b]	[c]65.0		72.6
1	62.0	71.6	74.0
2	61.4	71.4	74.2
3	64.4	67.7	72.9
4	60.8	70.8	74.2
5	60.8	69.5	73.1

[a]Average of five measurements
[b]Based on data from reference 3
[c]As-cast, not heat-treated



(a) Long necked.



(b) Short necked.

Figure 1. - Typical gas-turbine blades.

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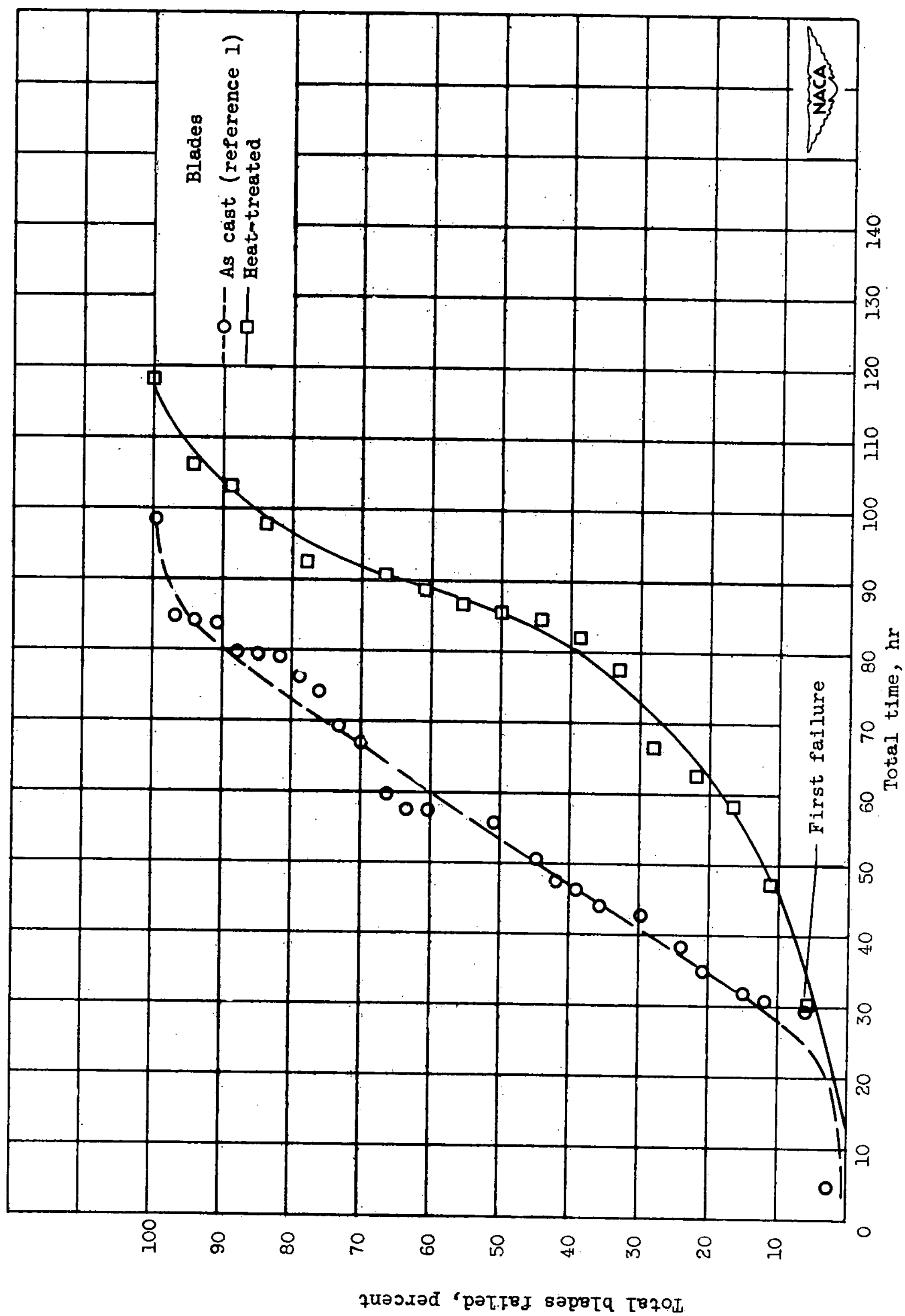
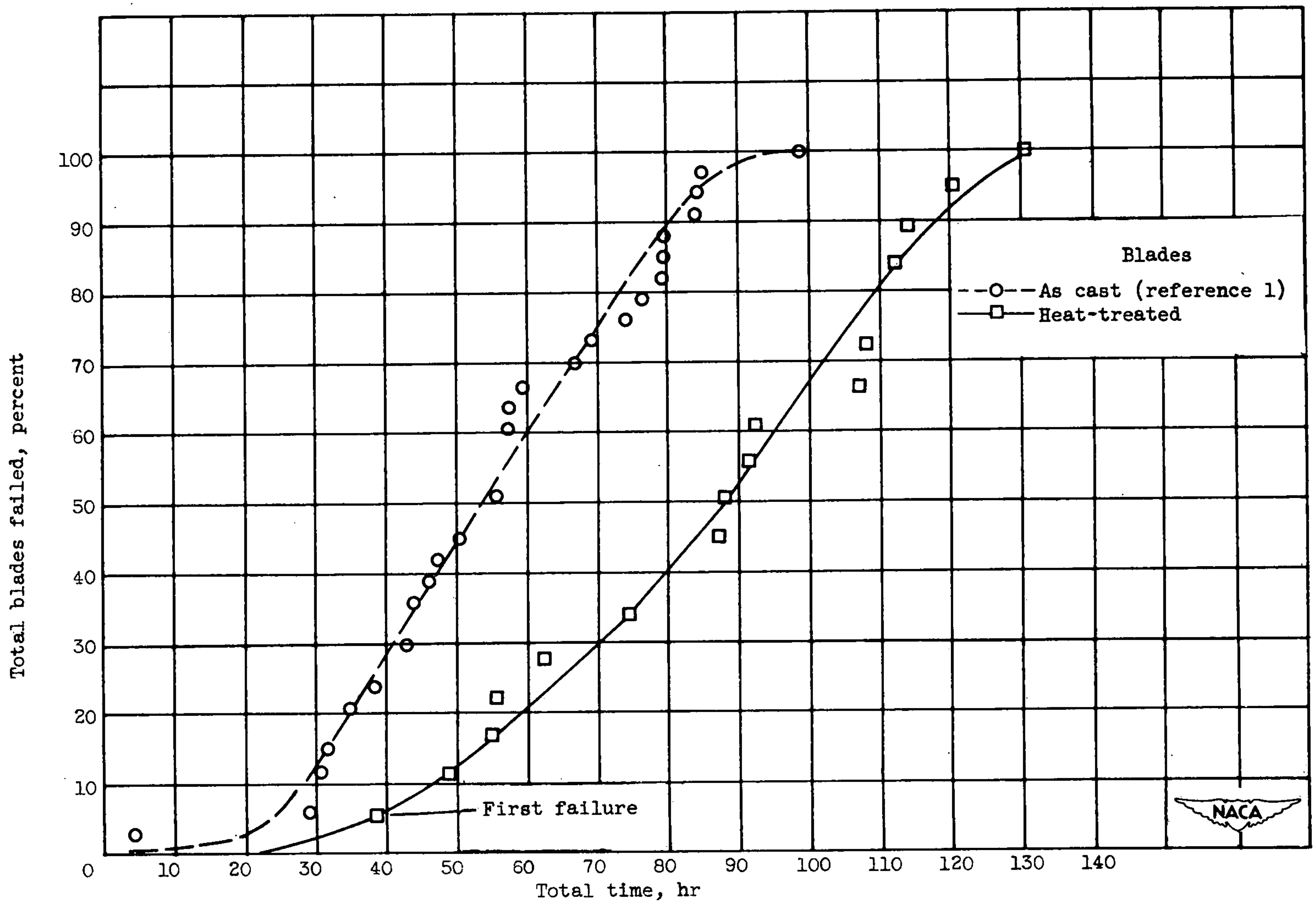


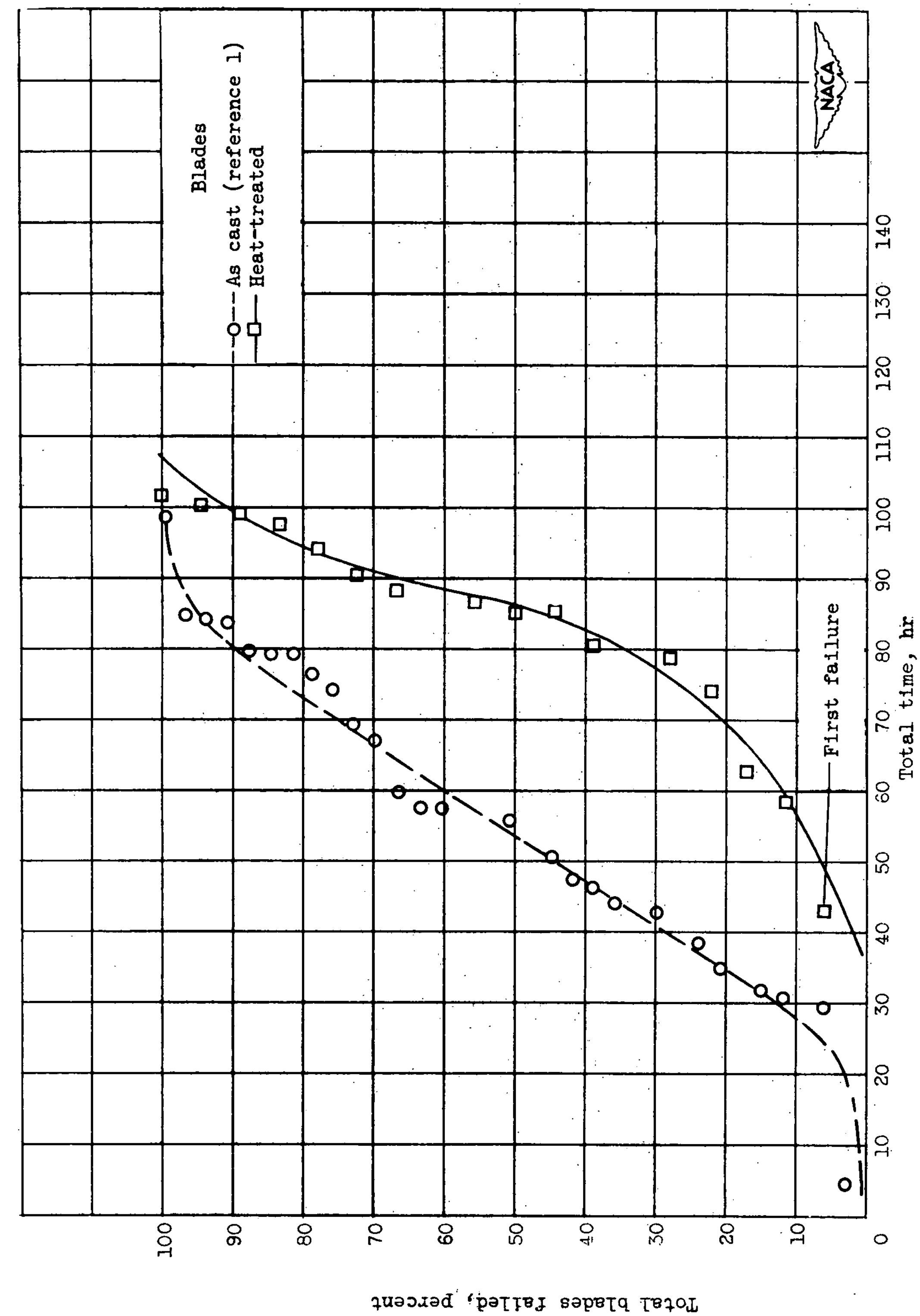
(a) Group 1: 1/2 hour at 2350° F, air-cooled, plus 48 hours at 1500° F.

Figure 2. - Cumulative-frequency curves for as-cast and solution-treated AMS 5385 blades.



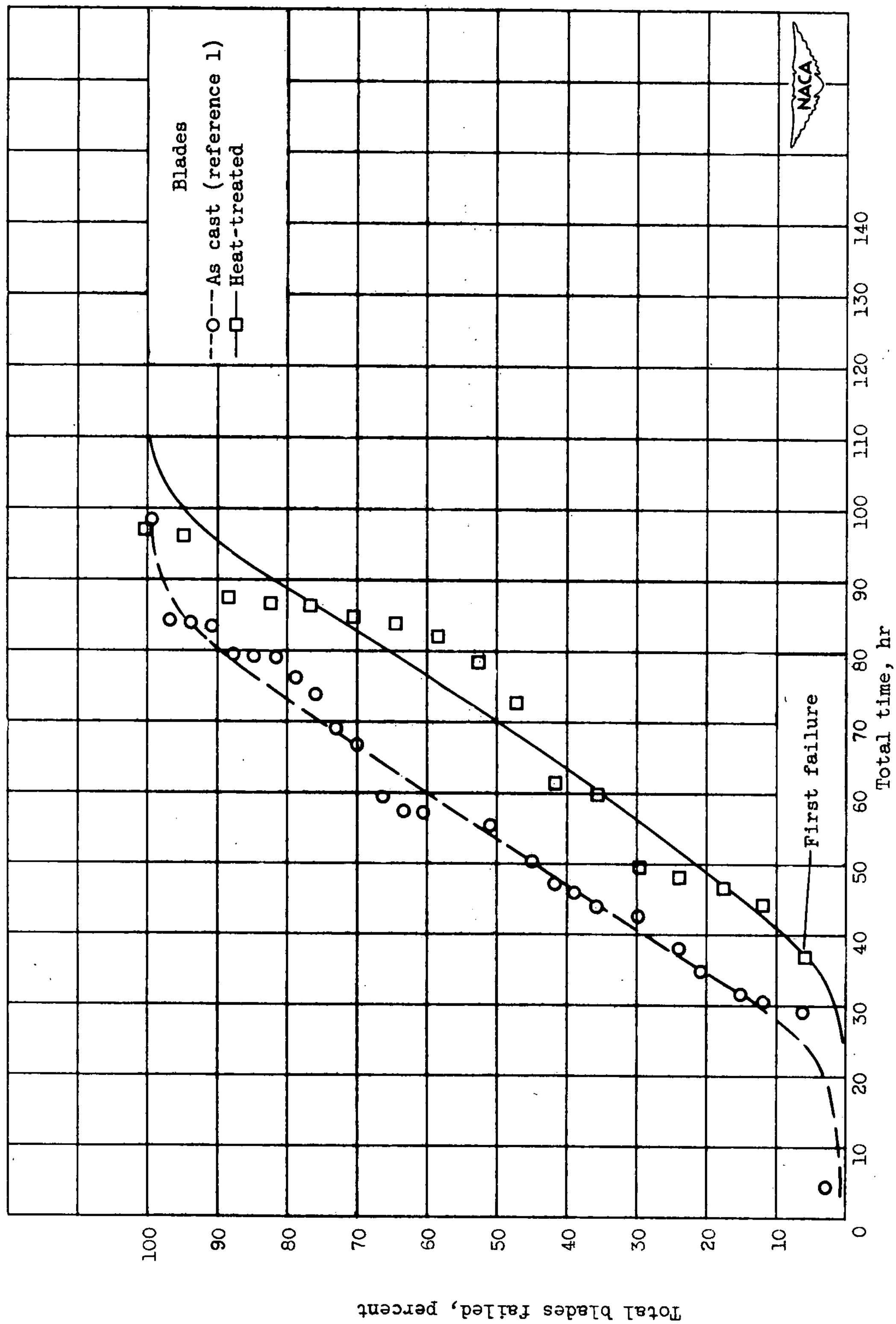
(b) Group 2: 1/2 hour at 2250° F, air-cooled, plus 48 hours at 1500° F.

Figure 2. - Continued. Cumulative-frequency curves for as-cast and solution-treated AMS 5385 blades.



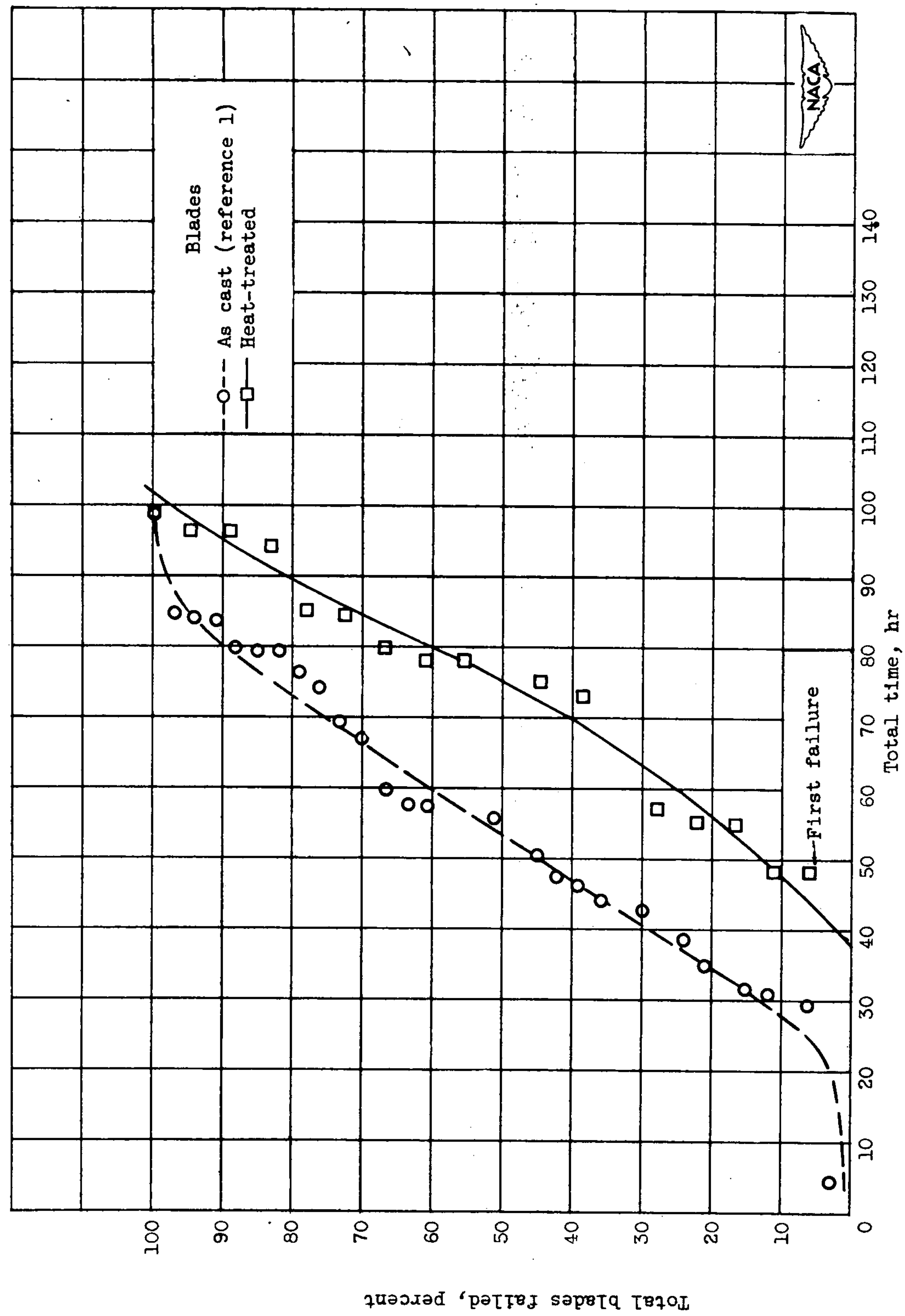
(c) Group 3: 1/2 hour at 2100° F, air-cooled, plus 48 hours at 1500° F.

Figure 2. - Continued. Cumulative-frequency curves for as-cast and solution-treated AMS 5385 blades.



(d) Group 4: 1/2 hour at 2350° F, furnace-cooled, plus 48 hours at 1500° F.

Figure 2. - Continued. Cumulative-frequency curves for as-cast and solution-treated AMS 5385 blades.



(e) Group 5: 1/2 hour at 2250° F, furnace-cooled, plus 48 hours at 1500° F.

Figure 2. - Concluded. Cumulative-frequency curves for as-cast and solution-treated AMS 5385 blades.

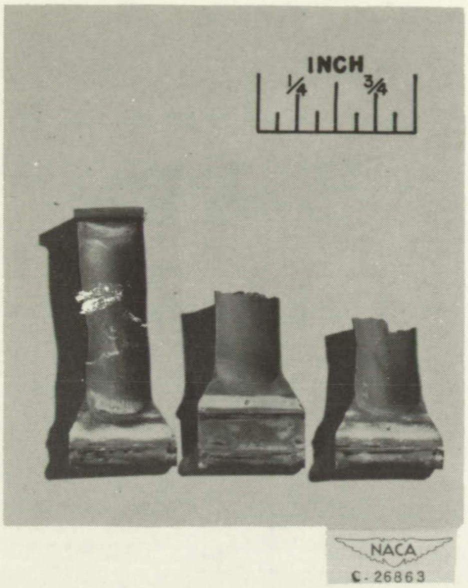


Figure 3. - Typical fractured and badly cracked AMS 5385 blades.

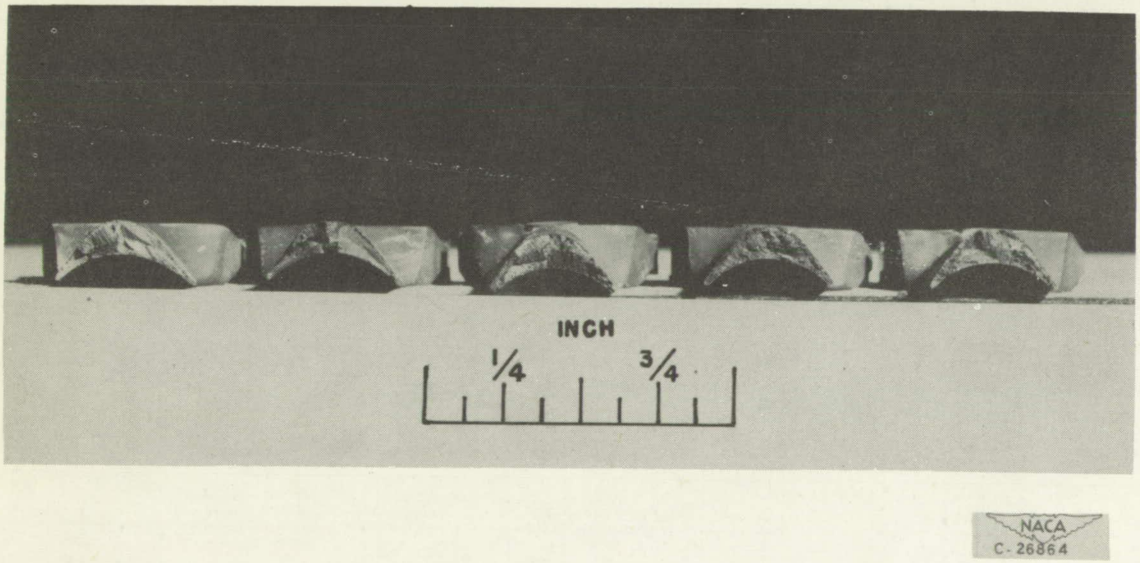


Figure 4. - Typical AMS 5385 blade-fracture surfaces.

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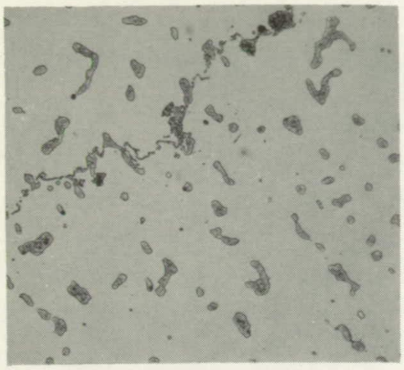
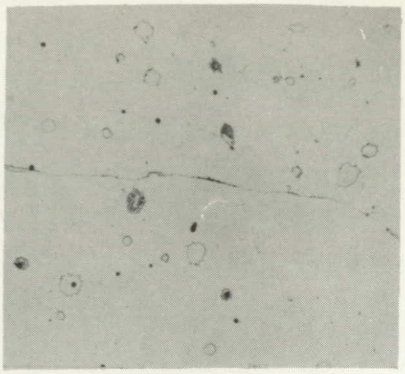
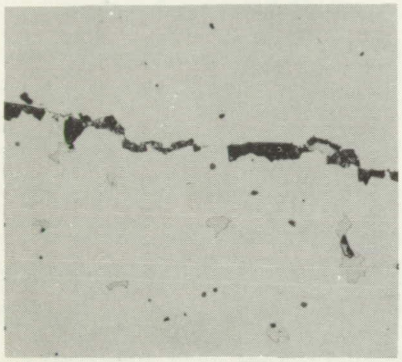


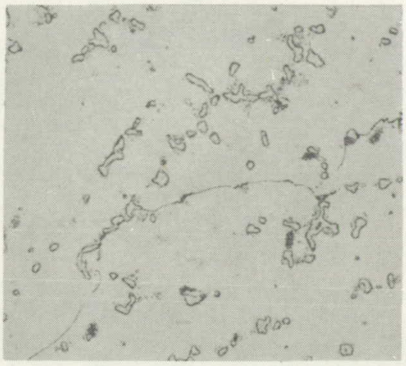
(a) As-cast



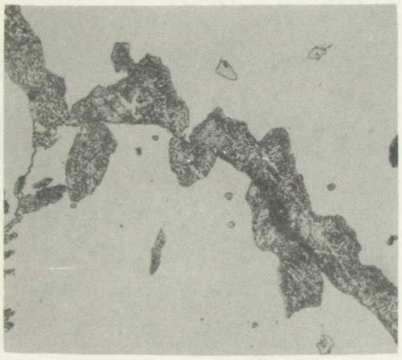
(b) Group 1: 1/2 hour at 2350° F, air-cooled.



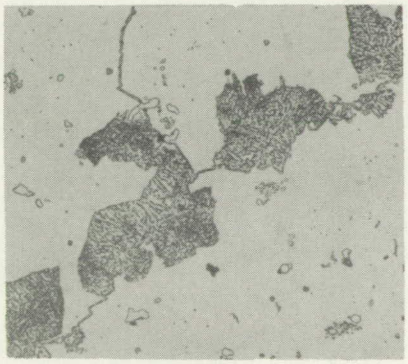
(c) Group 2: 1/2 hour at 2250° F, air-cooled.



(d) Group 3: 1/2 hour at 2100° F, air-cooled.



(e) Group 4: 1/2 hour at 2350° F, furnace-cooled.



(f) Group 5: 1/2 hour at 2250° F, furnace-cooled.

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Figure 5. - Solution-treated structures of AMS 5385 before aging. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. X250.

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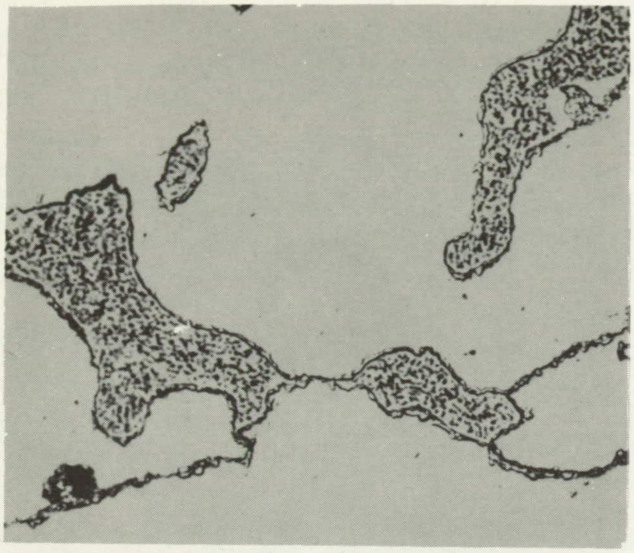

Figure 6. - Complex carbide in as-cast AMS 5385 before operation. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. X1500.

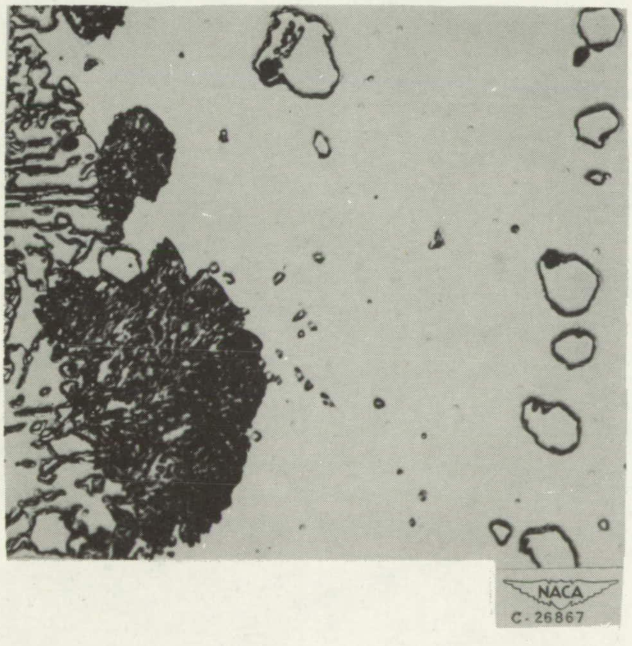

Figure 7. - Complex carbides in AMS 5385 after solution treatment for 1/2 hour at 2350° F and furnace cooling. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. X1000.

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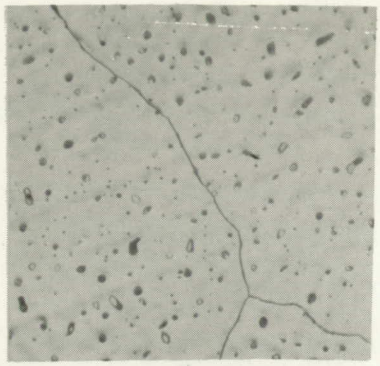
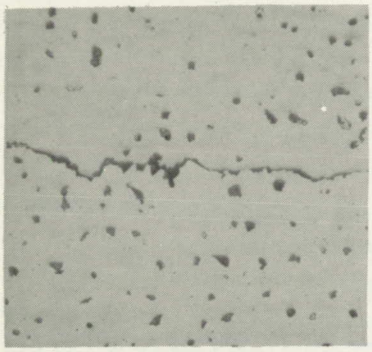
(a) As-cast

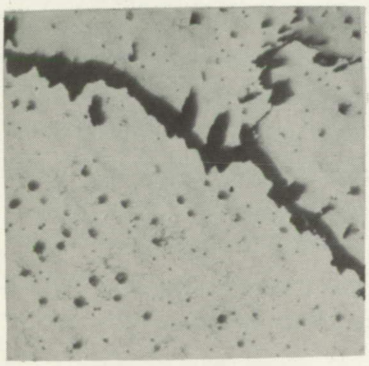


(b) Group 1: 1/2 hour at 2350° F, air-cooled.

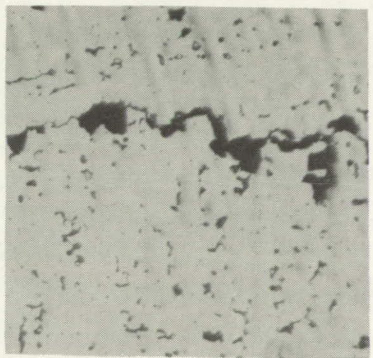


(c) Group 2: 1/2 hour at 2250° F, air-cooled.

(d) Group 3: 1/2 hour at 2100° F, air-cooled.



(e) Group 4: 1/2 hour at 2350° F, furnace-cooled.



(f) Group 5: 1/2 hour at 2250° F, furnace-cooled.

Figure 8. - Effect of solution treatment on degree of coring in cast AMS 5385. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. X100.

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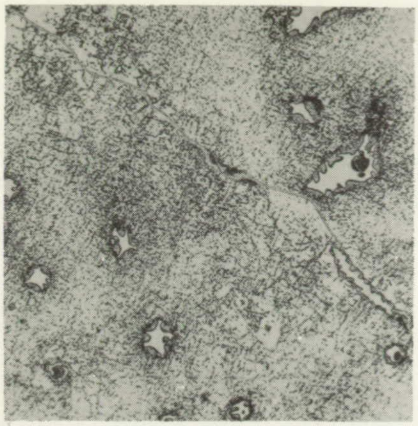
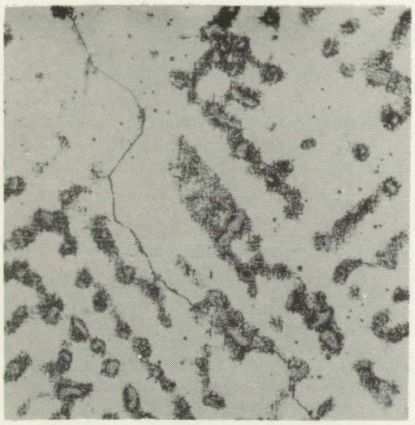
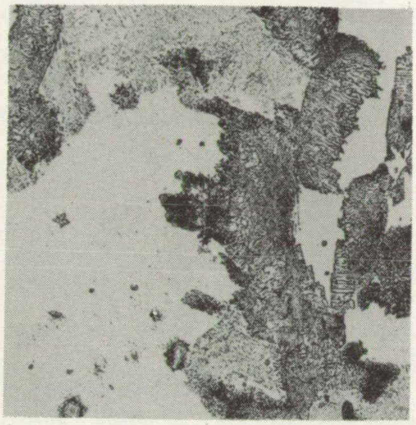


(a) Group 1: 1/2 hour at 2350° F, air-cooled.

(b) Group 2: 1/2 hour at 2250° F, air-cooled



(c) Group 3: 1/2 hour at 2100° F, air-cooled.



(d) Group 4: 1/2 hour at 2350° F, furnace-cooled.

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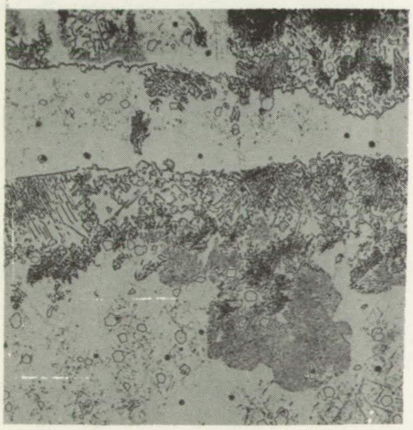

(e) Group 5: 1/2 hour at 2250° F, furnace-cooled.

Figure 9. - Solution-treated AMS 5385 blades after aging 48 hours at 1500° F. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. X250.

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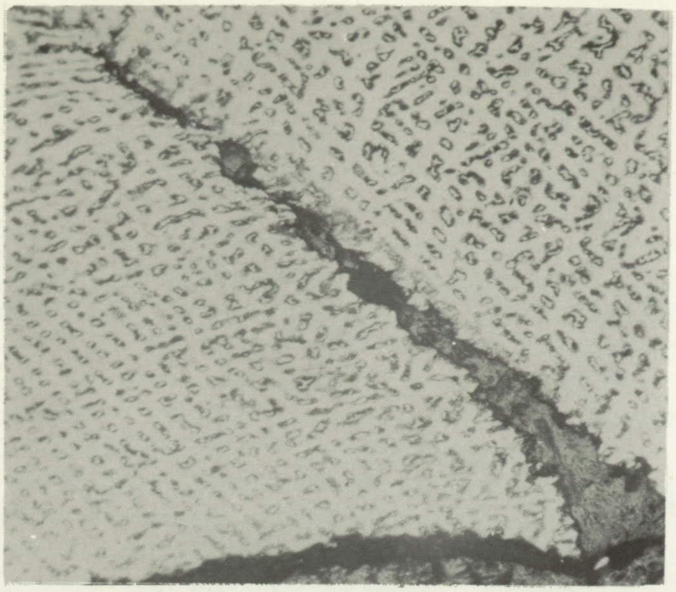
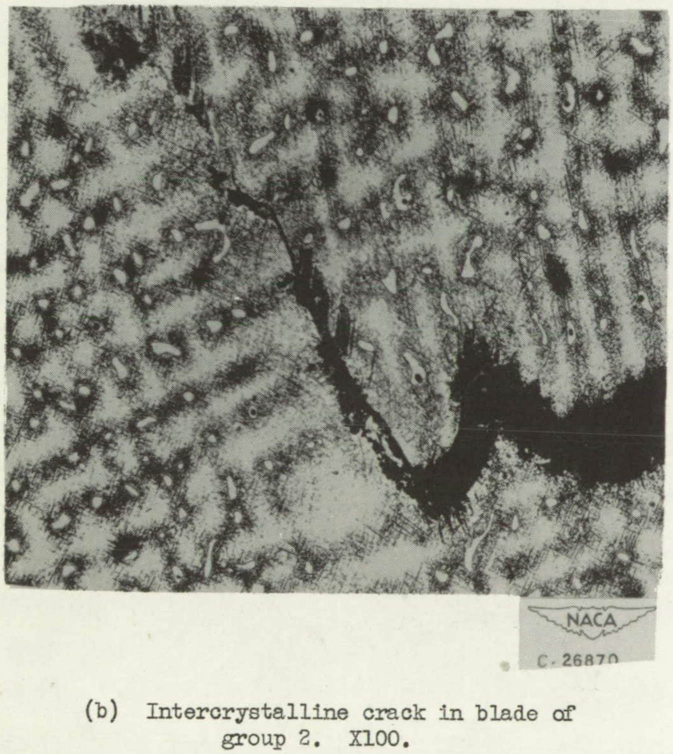


(a) Intercrystalline crack in blade of group 3. X50.



(b) Intercrystalline crack in blade of group 2. X100.

Figure 10. - Typical cracks in AMS 5385 blades. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol.

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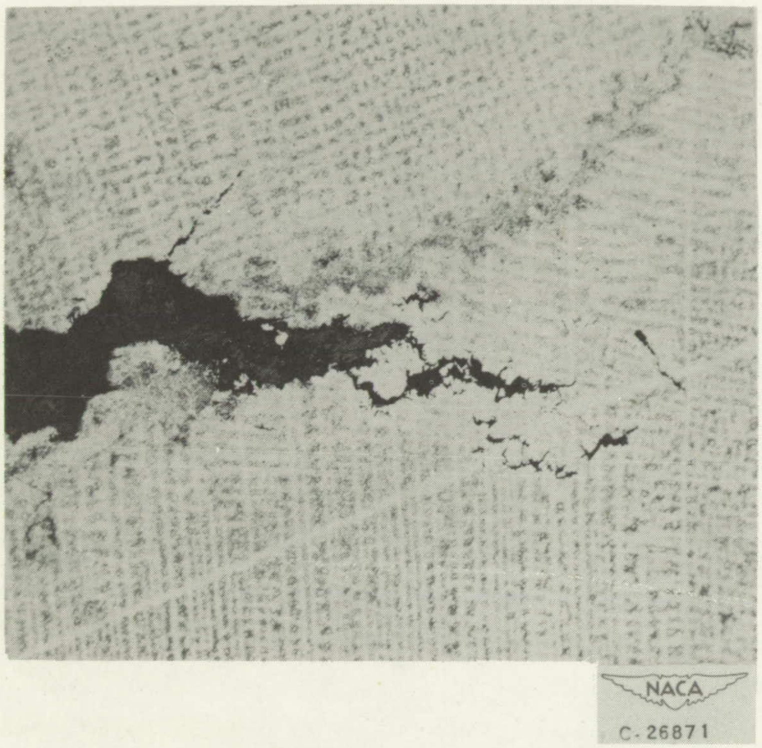

(c) Intercrystalline crack which has started to become transcrystalline in blade of group 4. X50.

Figure 10. - Concluded. Typical cracks in AMS 5385 blades. Electrolytically etched in 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol.

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